ground water

Combining Pump-and-Treat and Physical Barriers for Contaminant Plume Control

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Abstract

A detailed analysis is presented of the hydraulic efficiency of plume management alternatives that combine a conventional pump-and-treat system with vertical, physical hydraulic barriers such as slurry walls or sheet piles. Various design settings are examined for their potential to reduce the pumping rate needed to obtain a complete capture of a given contaminated area. Using established modeling techniques for flow and transport, those barrier configurations (specified by location, shape, and length) that yield a maximum reduction of the pumping rate are identified assuming homogeneous aquifer conditions. Selected configurations are further analyzed concerning their hydraulic performance under heterogeneous aquifer conditions by means of a stochastic approach (Monte Carlo simulations) with aquifer transmissivity as a random space function. The results show that physical barriers are an appropriate means to decrease expected (mean) pumping rates, as well as the variance of the corresponding pumping rate distribution at any given degree of heterogeneity. The methodology presented can be transferred easily to other aquifer scenarios, provided some basic premises are fulfilled, and may serve as a basis for reducing the pumping rate in existing pump-and-treat systems.

Introduction

Pump-and-treat is still the most common technology for the cleanup of ground water contamination (U.S. National Research Council 1999). However, the experience of recent decades confirms early warnings from Keely (1989) and Travis and Doty (1990) that with conventional practices aquifer restoration is not achievable within a short timeframe or at all if the contaminated source is not removed entirely. This is due to a limitation of mass transfer from residual contaminant phases into ground water leading to rather low contaminant release rates and consequently long lifetimes of the source (Hunt et al. 1988a, 1988b; Berglund and Cvetkovic 1995; Grathwohl 2000). It is commonly accepted that a complete source removal will only be possible in exceptional cases, even if there exists a substantial potential to tackle the source zone by in situ source treatment technologies. Therefore, in spite of short-term source treatment measures, a long-term plume management will be still required for the majority of contaminated sites. With this background in mind, we regard pump-and-treat as a long-term plume management method to control contaminant spreading, rather than as a remediation technology aiming at full aquifer restoration within a reasonable timeframe. As a long-term measure, operational costs for pump-and-treat must be minimized to achieve cost efficiency. Here, efficiency refers to the hydraulic effect of the pump-and-treat measure, i.e., the control of the contamination disregarding the amount of contaminant mass removed. Since pumping and on-site treatment costs are directly related to the pumping rate, a reduction of operational costs requires a reduction of the pumping rate that is necessary to guarantee plume control (capture).

In this paper, we examine the potential of partial containment strategies to reduce the pumping rate required for the pump-and-treat measure by the installation of physical barriers such as slurry walls or sheet piles. Different barrier settings (specified by location, shape, and length of the barrier) are analyzed with respect to their effect on the pumping rate within the framework of a modeling study on a

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simplified contamination scenario. Respective settings are represented by means of a ground water flow model. Particle tracking is employed to evaluate contaminant capture. Homogeneous, as well as heterogeneous, aquifer conditions are studied.

Previous Work

Impermeable hydraulic barriers have been a common means of ground water remediation for decades (Knox 1984; Barker et al. 1994; Bardos and van Veen 1996; Marryot 1996). Although physical barriers such as slurry walls or sheet piles have repeatedly been suggested as a possible enhancement of conventional pump-and-treat in the past (U.S. Environmental Protection Agency 1996; U.S. National Research Council 1997), only a few papers have examined the effectiveness of such a combined semipassive system by means of hydraulic models.

Ahlfeld et al. (1987) presented a method for determining the most effective ground water withdrawal method, considering a selective application of physical containment to the upgradient part of a given contaminant plume coupled with pumping wells to capture the downgradient part of the plume. The objective was to reduce the contaminant concentration to a minimum level at selected points downgradient of the pumping wells, i.e., to achieve the maximum plume remediation within a given planning period. They applied a numerical transport model, which is required if concentration values are used as a decision criterion. However, the usefulness of transport models often suffers from the fact that a comparatively large set of input data is required, which is only partially known. This refers especially to the knowledge of the spatial distribution of physicochemical aquifer properties and contaminant concentration, and results in considerably uncertain outcomes of the system optimization.

Mulligan and Ahlfeld (1999) discuss these problems within the framework of optimization of conventional pump-and-treat systems. They propose the advective control approach, which stipulates the use of particle tracking instead of transport modeling to assess the effect of pump-and-treat measures with regard to source and/or plume control, neglecting pore-scale dispersion processes of contaminant transport.

Gupta et al. (1992) investigated the effects of hydraulic barriers on the hydraulic control during surfactant flushing at a contaminated site. The purpose was to reduce the demand for surfactant solution for an injection/extraction system by focusing the circular flow through a dense non-aqueous phase liquid source without loss to the surrounding aquifer. The comparison of numerically simulated flow patterns showed that hydraulic barriers could efficiently deflect the flow of surfactants into targeted zones and reduce the required pumping and injection rates.

In a modeling study regarding a real site, Bowen and Johnson (1993) examined the efficiency of five different slurry wall settings and concluded that no remarkable cost savings can be expected by implementing slurry walls in addition to a pump-and-treat system. The slurry walls were positioned upgradient and centrally at the predefined contour of a given contaminant plume. The objective was to optimize each setting by minimizing the total pumping rate of a group of wells inside a contaminated area that would prevent any further expansion of the contamination. The optimization was based on hydraulic control as described by Greenwald (1998), where head constraints are imposed at control points around the contamination in order to create inward-pointing gradients. Contrary to capture zone adaptation by particle tracking, this approach is strictly suitable for cases where the flow regime of the optimal system can be predicted accurately, such as in homogeneous aquifers. Ahlfeld et al. (1995) report further limitations of hydraulic control applications that might lead to apparently optimized systems with insufficient containment or excessive pumping.

The design of pump-and-treat systems for aquifer or ground water remediation technologies has also been investigated for heterogeneous aquifers. A common approach is to analyze design alternatives using a Monte Carlo simulation for a bulk of realizations of the spatial distribution of hydraulic conductivity in order to express the performance uncertainty (Freeze et al. 1980; Massmann and Freeze 1987; Wagner and Gorelick 1989; Chan 1993; Freeze and Gorelick 1999). We follow this approach with the subsequently presented hydraulic analysis of combining pump-and-treat with physical barrier systems.

Hydraulic Analysis

Methodology

A steady-state ground water flow model that represents the hydrogeological situation of the site to be investigated serves as the basis for the hydraulic analysis. Barrier settings are implemented systematically in order to examine the effect of shape, length, and location of the barriers. The simulation software MODFLOW (McDonald and Harbaugh 1988) was used for the flow calculations. Physical barriers have been implemented by utilization of the horizontal flow barrier package of MODFLOW. The respective combined pump-and-treat and physical barrier systems are then analyzed by repeatedly performing two steps. First, the effect of the remediation system on the ground water flow conditions is modeled. Second, similar to the advective control approach of Mulligan and Ahlfeld (1999), a particle-tracking algorithm, MODPATH (Pollock 1994), is used to examine whether the current design guarantees complete capture of the contaminated area to be controlled. This is done by tracking particles, starting from the edge of the contaminated area, along the flow lines. Complete capture is affirmed if all particles ended up in a well cell. Wells are specified as distributed sinks that capture particles only if they are representing a strong sink. It should be noted that the representation of well capture zones by means of particle tracking is an approximation. The quality of this approximation depends on the chosen model discretization and number of particles. For each barrier setting, the optimal pumping rate, Q_m, is determined. The variable Q_m is the minimum total pumping rate required for complete plume control. A single extraction well or an array of wells may be considered. Although there is obviously substantial potential to improve the system efficiency by optimizing the number and spatial configuration of the pumping well(s), we wish to limit our analysis in this paper to a single well with a predefined (fixed) location. This is not a limitation of the approach or the optimization method used, but serves to narrow the decision space in order to direct the attention to the analysis of the benefit of partial containment designs. In this case, Q_m can be determined by repeated model runs using the bisection method (Press et al. 1992).

In contrast to others (Bowen and Johnson 1993), our objective is to control the contaminant source and plume by extracting ground water a certain distance downgradient from the source. In comparison to source control with pumping wells located within the source zone, downgradient plume control requires much lower pumping rates and is therefore preferable for long-term control of a ground water contamination (Bayer et al. 2002).

Designing pump-and-treat systems in natural aquifers means that one has to account for uncertainty arising from sparse information on the spatial distribution of relevant properties. As a result, the prediction is equally uncertain. In contrast to deterministic approaches that result in a definite value of Q_m, the Monte Carlo simulation accomplished here reflects the prediction uncertainty with respect to Q_m by means of a probability distribution of Q_m. In this paper, we limit our investigations to the transmissivity uncertainty, as transmissivity, T, is the major factor affecting the extent of the pumping well capture zone (Franzetti and Guadagnini 1996). In order to describe the incomplete knowledge of T, it is modeled as a random space function. We assume that only the statistical moments of the spatial distribution of T are known and perform unconditional simulations of T. The hydraulic transmissivity patterns are generated stochastically by means of a sequential Gaussian field generator as described by Deutsch and Journel (1992). A log-normally distributed transmissivity $Y = \ln\overline{T}(x)$ with fluctuations of zero mean and variance, $\sigma_Y{}^2$, is considered. The spatial correlation of Y is described by the integral scale I_Y, introduced by the two-point covariance function:

$$C_Y(\mathbf{h}) = \sigma_Y^2 \exp\left(\frac{-|\mathbf{h}|}{I_Y}\right) \quad (1)$$

where **h** is the lag separation vector. Assuming isotropy and stationarity, the parameters $\sigma_Y{}^2$ and I_Y are sufficient for complete characterization of the spatial distribution of T. Consistent with previous work on the shape of well protection zones (Franzetti and Guadagnini 1996; van Leeuwen et al. 2000; Feyen et al. 2001), the results are reported as a function of these parameters. However, it has to be mentioned that the concepts described by Franzetti and Guadagnini (1996) and van Leeuwen et al. (2000) differ from the one applied here. They studied the delineation of the capture zone for given statistical aquifer parameters and a predefined pumping rate. Uncertainty was expressed by means of spatial distributions of capture probability. In this paper, the uncertainty analysis is based on an inverse approach; i.e., the probability of minimum pumping rate, Q_m, necessary to establish a given capture area is calculated. Since Q_m has to be determined iteratively with repeated model runs for each realization, the approach followed here needs more computations, but it appears to be more suitable to practical remediation problems where the extent of the contaminated area to be captured is known or estimated, and may serve directly as a decision criterion.

Having calculated Q_m for each aquifer realization z, the hydraulic analysis results in a series of values of $Q_{m,z}$ (z = 1, . . . , total number of realizations). This series can then be used to determine the reliability measure R (with respect to complete plume control) of the remediation scenario (barrier setting) under consideration for any given pumping rate Q as the percentage of realizations that yield a $Q_{m,z}$ lower than Q:

$$R = F(Q) = \frac{\textit{Number of realizations with } Q_{m,z} \le Q}{\textit{Total number of realizations}} \quad (2)$$

where F(Q) represents the cumulative distribution function of pumping rate Q.

Reference Scenario—Conventional Pump-and-Treat

In this paper, no specific site conditions are addressed, but a simple ground water contamination scenario is used to demonstrate the application of combined pump-and-treat-barrier systems. This should reveal whether combined systems have significant advantages in comparison to conventional pump-and-treat systems. For this demonstration, a steady-state two-dimensional ground water flow domain with a quadratic dimension of 300 m by 300 m is considered (Figure 1). Assuming confined conditions, a uniform regional flow gradient pointing from north to south is set by constant head boundaries. No-flow conditions were selected at the eastern and western boundaries. A regular grid spacing of 1 m by 1 m cells is used. A total of 200 particles arranged equispaced in a row along a square in the center of the model region delineate the boundary of the

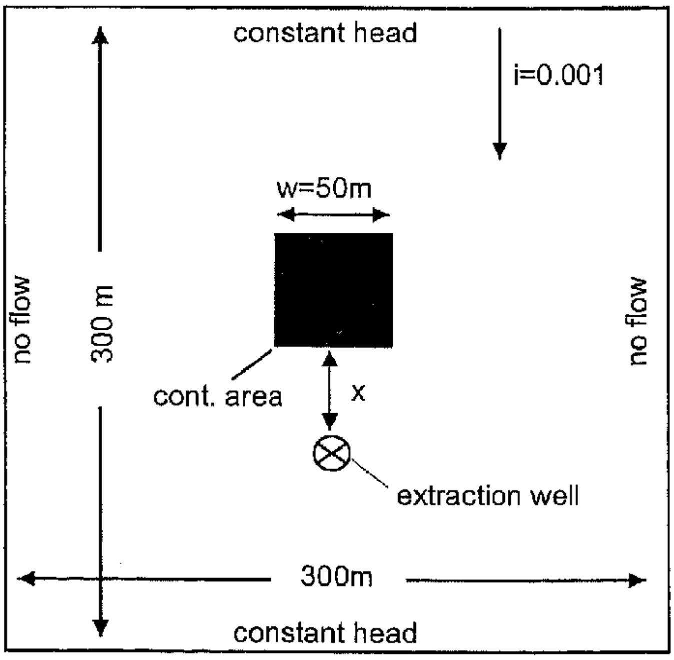

Figure 1. Schematic illustration of the model setup.

contaminated area (source zone), which has a quadratic dimension of 50 m by 50 m. The pumping well can be located in central position at any certain distance x downgradient of the source zone. This scenario A will be referred to as the CPT (conventional pump-and-treat) scenario.

To ensure that the model setup is appropriate in terms of the extent of the model region in relation to the length scale of the hydraulic effects imposed by the pumping well and the physical barriers (as listed later), various preliminary simulations were performed with model domains of different sizes. The results showed that boundary effects can be neglected for the chosen dimensions. Furthermore, the aptness of the chosen discretization with respect to the quality of the particle tracking-based capture zone calculation was verified for the CPT scenario by comparing numerically calculated pumping rates $Q_m(x)$ with the respective analytical solutions after Javandel and Tsang (1986). Differences were below 1% and assumed to be insignificant for the purpose of this work.

It should be noted that the steady-state approach used here implies that particles begin migration only after the pump is turned on. Any propagation of the contaminants that took place before pumping within the undisturbed flow field is not explicitly taken into consideration. The long-term objective of control by the pumping well is assumed to be targeted to the source area and any further contaminant migration downgradient of this area. Any part of a potentially existing plume that lies outside the capture zone of the well is not subject to control.

Scenarios with Barriers

Since the number of possible barrier settings is infinite, it is obviously not possible to address them all in a systematical and comprehensive manner. Therefore, this study is limited to a subset of the possible settings, i.e., those that proved to be the most favorable, as identified within a preliminary study by Bayer (1999). The investigation is restricted to symmetrical configurations with barriers placed along the boundary of the quadratic contaminated area. For the sake of clarity, they are grouped into four scenarios (Figure 2). Scenario B has one barrier at the upgradient edge of the contaminated area; scenario C has one barrier at the downgradient edge; scenario D has two barriers, one at the upgradient edge and one at the downgradient

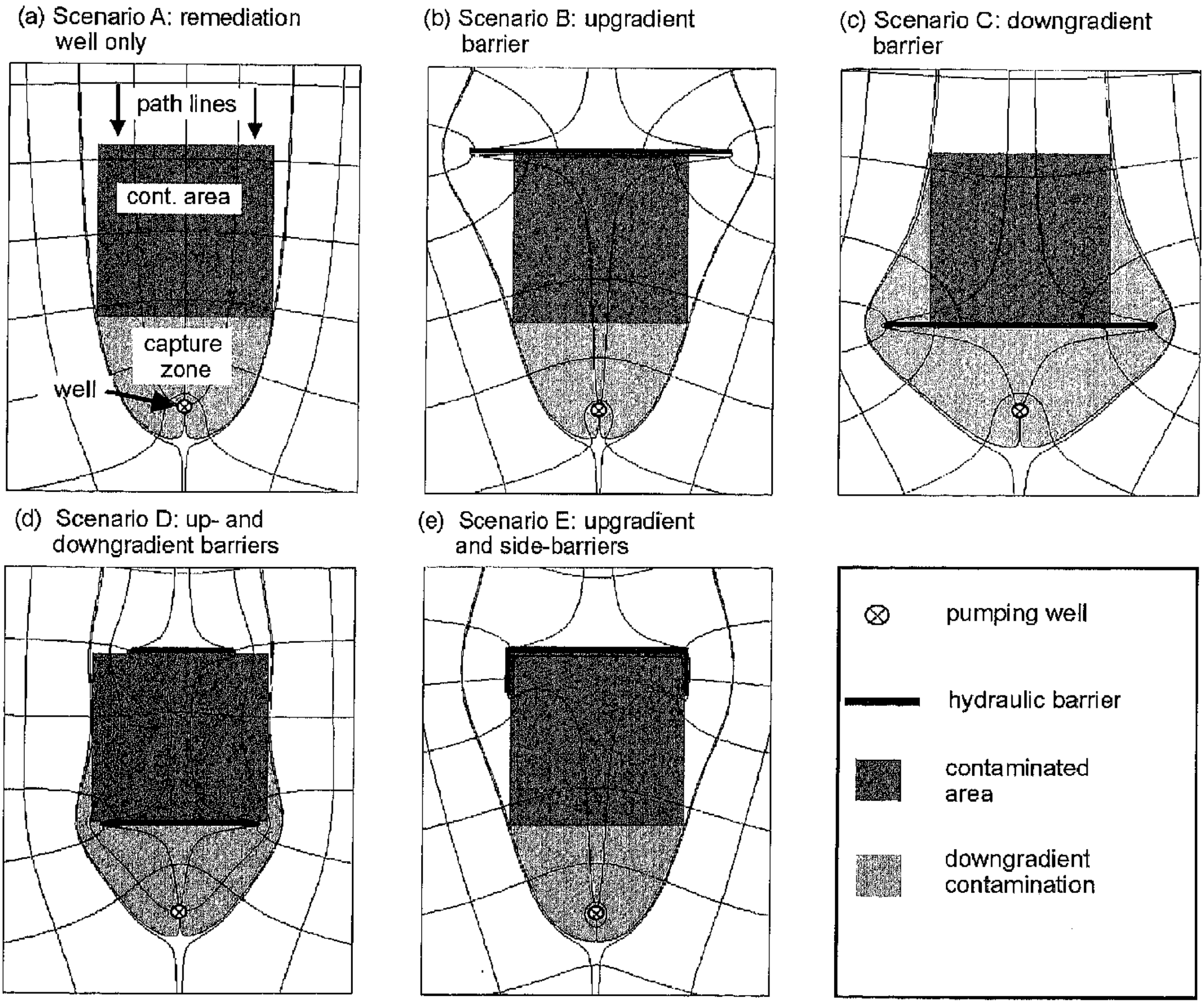

Figure 2. Scenarios with geometric arrangement of active and passive control systems.

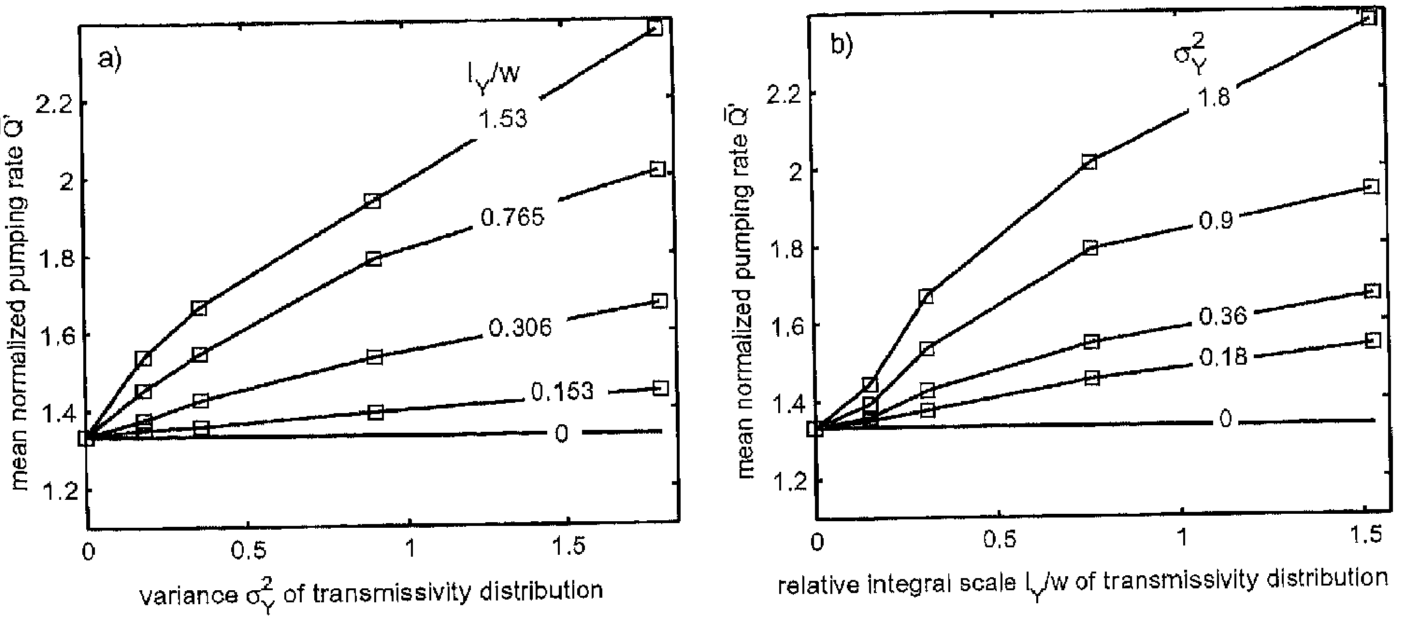

Figure 6. Scenario A—calculated mean normalized pumping rates, $\overline{Q'}$, depending on the type of the unconditioned transmissivity distribution of the aquifer (for ensembles of 500 realizations).

Heterogeneous Aquifer Conditions

In order to evaluate the sensitivity of the Q_z' distributions to the degree of aquifer heterogeneity, seven different ensembles of 500 aquifer realizations each were examined. The dataset is based on the statistical parameters σ_Y^2 and I_Y determined at the Borden Aquifer in Ontario, Canada (Sudicky 1986; Burr et al. 1994): $\sigma_{Y,Bo}^2 = 0.18$, $I_{Y,Bo} = 15.3$ m. An ensemble representing a comparatively small transmissivity heterogeneity ($\sigma_{Y,1}^2 = \sigma_{Y,Bo}^2 = 0.18$, $I_{Y,1} = 0.5$, $I_{Y,Bo} = 7.65$ m; with w = 50 m: $I_{Y,1}/w = 0.153$) was analyzed first. Then, in order to examine the effect of aquifer heterogeneity, values of σ_Y^2 and I_Y were successively increased. The following data values were investigated: $I_{Y,1}/w = 0.153$, $I_{Y,2}/w = 0.306$, $I_{Y,3}/w = 0.765$, $I_{Y,4}/w = 1.53$, $\sigma_{Y,1}^2 = 0.18$, $\sigma_{Y,2}^2 = 0.36$, $\sigma_{Y,3}^2 = 0.9$, $\sigma_{Y,4}^2 = 1.8$.

To reduce the number of decision variables, the distance between the well and the edge of the contaminated area was fixed at x/w = 0.5. Furthermore, the analysis of BPT scenarios was limited to certain settings with a given total barrier length as follows. Setting B* = scenario B with b/w = 1 (barrier along the complete upgradient boundary of the contaminated area). Setting C* = scenario C with b/w = 1 (barrier along the downgradient boundary). Setting D* = scenario D with b/w = 2 (one barrier along the upgradient boundary, one barrier along the downgradient boundary; $b_{up} = b_{down} = w$). Setting E* = scenario E with b/w = 3 (barrier along the upgradient boundary and the sides of the contaminated area).

The results for CPT show that increasing the values of either σ_Y^2 or I_Y leads to a significant rise of the mean pumping rate, $\overline{Q'}$ (Figures 6a and 6b). The sensitivity of

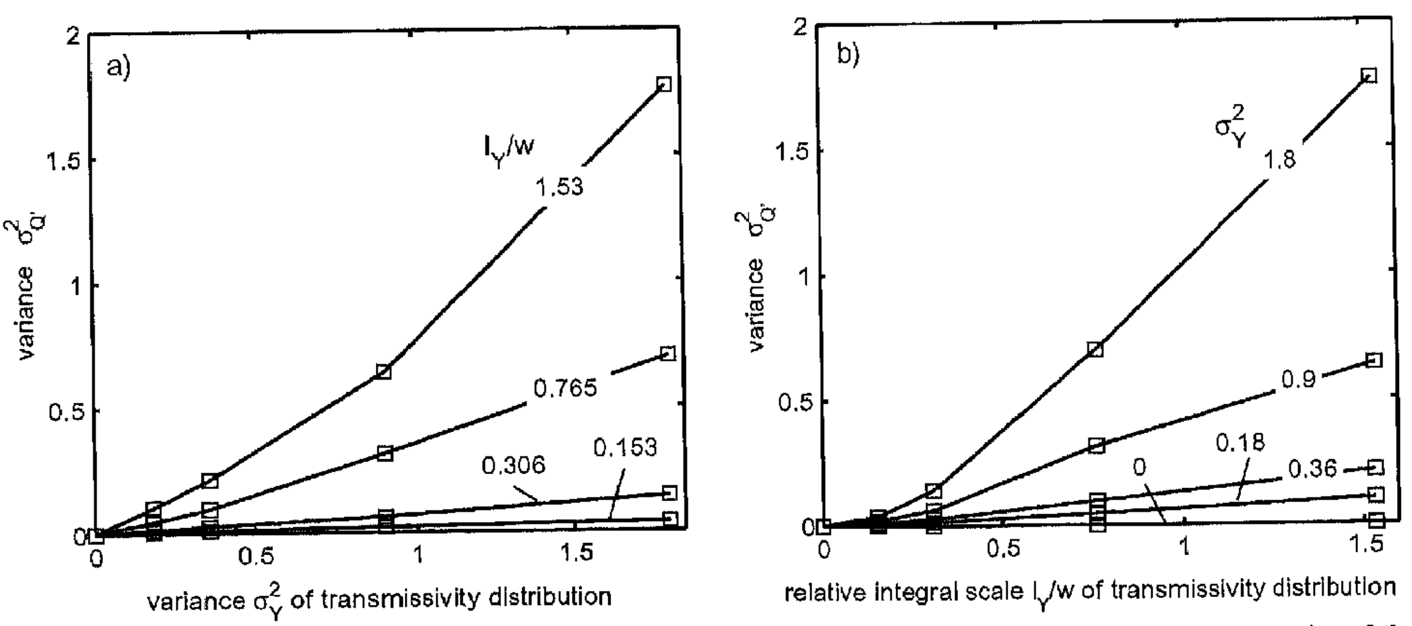

Figure 7. Scenario A—calculated variance, $\sigma^2_{Q'}$, depending on the type of the unconditioned transmissivity distribution of the aquifer (for ensembles of 500 realizations).

$\overline{Q'}$ to the degree of heterogeneity appears to be highest for relatively low values of σ_Y^2 and I_Y. A different behavior is observed for the pumping rate variance $\sigma^2_{Q'}$ (Figures 7a and 7b), which progressively increases for high values of σ_Y^2 and I_Y. Comparing these results with the homogeneous case, it becomes evident that even in the case of a relatively slight heterogeneity, uncertainty with respect to the spatial transmissivity distribution will require a remarkable amount of over-pumping to ensure that the hydraulic containment of a given contaminant area is achieved. For any given degree of heterogeneity, the extent of this extra pumping will depend on the reliability level desired for the given measure (Teutsch and Hofmann 1990; Freeze and Gorelick 1999).

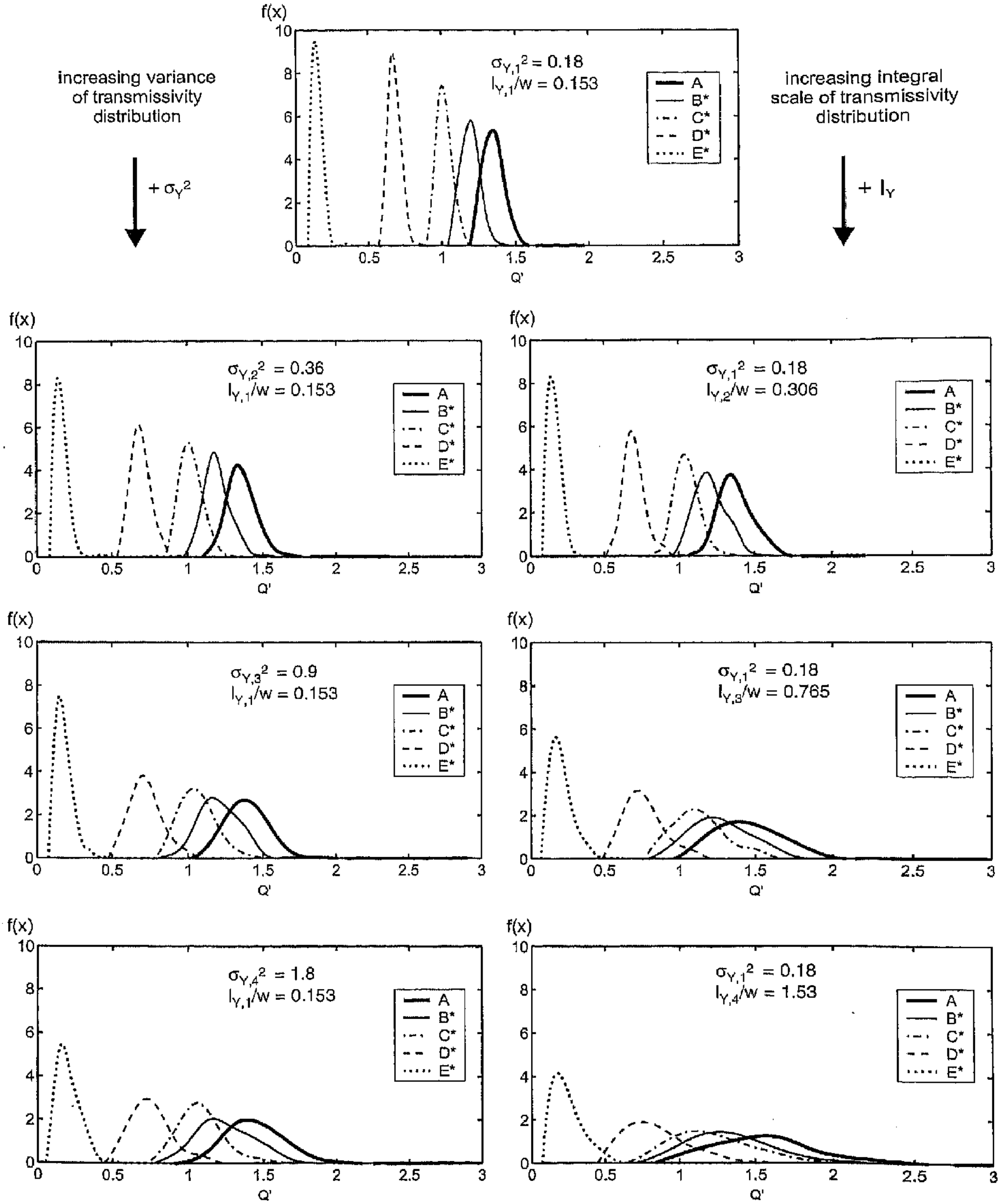

Figure 8. Pdfs of Q′ for scenario A and settings B*–E* for increase of σ_Y^2 and I_Y as a result of the Monte Carlo analysis.

Table 1
Mean and Variance ($\overline{Q'}$, $\sigma_{Q'}^2$) of Normalized Pumping Rates for Increasing Variance of the Lognormal Transmissivity Distribution (σ_Y^2 = 0.18 to 1.8; I_Y/w = 0.153)

	Setting	Homog.	Variance σ_Y^2 0.18	0.36	0.9	1.8
$\overline{Q'}$	A	1.31	1.33	1.34	1.37	1.42
	B*	1.19	1.19	1.19	1.21	1.25
	C*	0.98	1.02	1.02	1.06	1.08
	D*	0.62	0.66	0.67	0.70	0.74
	E*	0.12	0.14	0.16	0.17	0.20
$\sigma_{Q'}^2$	A*		0.005	0.009	0.020	0.037
	B*		0.004	0.008	0.018	0.036
	C*		0.003	0.005	0.014	0.023
	D*		0.002	0.004	0.012	0.020
	E*		0.002	0.003	0.003	0.006

Table 2
Mean and Variance ($\overline{Q'}$, $\sigma_{Q'}^2$) of Normalized Pumping Rates for Increasing Integral Scale of the Lognormal Transmissivity Distribution (I_Y/w = 0.153 to 1.53; σ_Y^2 = 0.18)

	Setting	Homog.	Integral Scale I_Y/w 0.153	0.306	0.765	1.53
$\overline{Q'}$	A	1.31	1.33	1.36	1.44	1.53
	B*	1.19	1.19	1.21	1.27	1.33
	C*	0.98	1.02	1.05	1.13	1.22
	D*	0.62	0.66	0.68	0.76	0.83
	E*	0.12	0.14	0.16	0.20	0.24
$\sigma_{Q'}^2$	A		0.005	0.012	0.045	0.101
	B*		0.004	0.011	0.039	0.079
	C*		0.003	0.007	0.031	0.078
	D*		0.002	0.005	0.018	0.046
	E*		0.002	0.002	0.006	0.012

With regard to the analysis of the BPT scenarios, i.e., of the potential of additional barriers, three aspects are of main importance: (1) the reduction of the mean pumping rate, $\overline{Q'}$, (2) the reduction of the pumping rate variance, $\sigma_{Q'}^2$, and (3) the probability that a certain BPT scenario yields lower Q′ values. Figure 8 and Tables 1 and 2 show that the ranking of the pump-and-treat scenarios with respect to the mean of Q′, $\overline{Q'}$, is independent of the level of heterogeneity. For all settings (A to E*) the variance of Q′, $\sigma_{Q'}^2$, grows with increasing I_Y or σ_Y^2, respectively. However, all BPT scenarios treated here (B* to E*) narrow $\sigma_{Q'}^2$ compared to the CPT scenario A. Obviously, the selected maximum values of I_Y stimulate higher sensitivities of both $\sigma_{Q'}^2$ and $\overline{Q'}$ as is the case for maximum σ_Y^2. Furthermore, a slight shift to generally higher Q′ values and an increasing positive skewness of the pdfs can be observed with rising I_Y or σ_Y^2 for all settings. This is illustrated in Figure 9 for settings A and D* at an integral scale I_Y/w = 0.765. Here, the growing spread and asymmetry of the pumping rate distribution with increasing σ_Y^2 is demonstrated in comparison to the homogeneous case (σ_Y^2 = 0).

It is worth noting that the benefit from BPT systems in terms of absolute reduction of mean pumping rate compared to CPT appears almost constant as either the variance (Table 1) or the integral scale (Table 2) is increased. At the same time, the increase of the variance, $\sigma_{Q'}^2$, of the ensemble's pumping rate distribution is much lower for any BPT than for the CPT system (Tables 1 and 2). However, the influence of I_Y/w and σ_Y^2 on the performance of any BPT compared to CPT is interrelated. Taking scenario D* as an example (Figure 10), this is shown in Table 3 where the values of the absolute reduction of mean pumping rate compared to CPT, $\Delta\,\overline{Q'}_{A\text{-}D*}$, are listed for the whole array of I_Y/w and σ_Y^2 values. For σ_Y^2 = 0.18, the case depicted in Figure 8 (right column), nearly no change of $\Delta\,\overline{Q'}_{A\text{-}D*}$ can be observed. For σ_Y^2 = 1.8, however, $\Delta\,\overline{Q'}_{A\text{-}D*}$ increases with I_Y/w from 0.69 to 0.89. Additional BPT model runs not shown here verify that, with increasing heterogeneity, there is a constant or accelerated reduction in mean pumping rate.

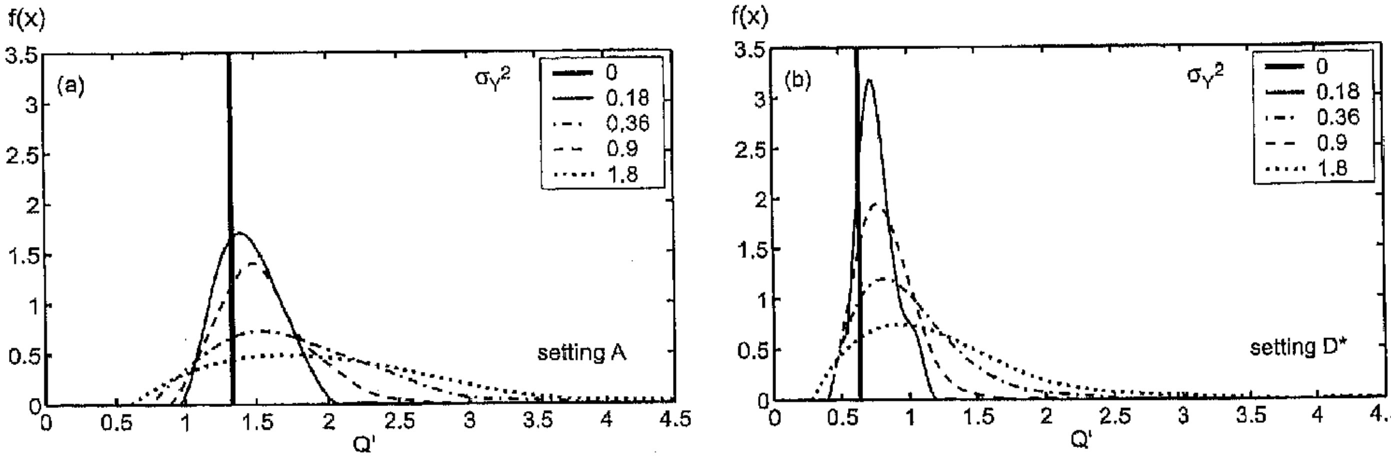

Figure 9. Pdfs of Q′—comparison between CPT (scenario A) and BPT (setting D*) for variable σ_Y^2 (I_Y/w = 0.765).

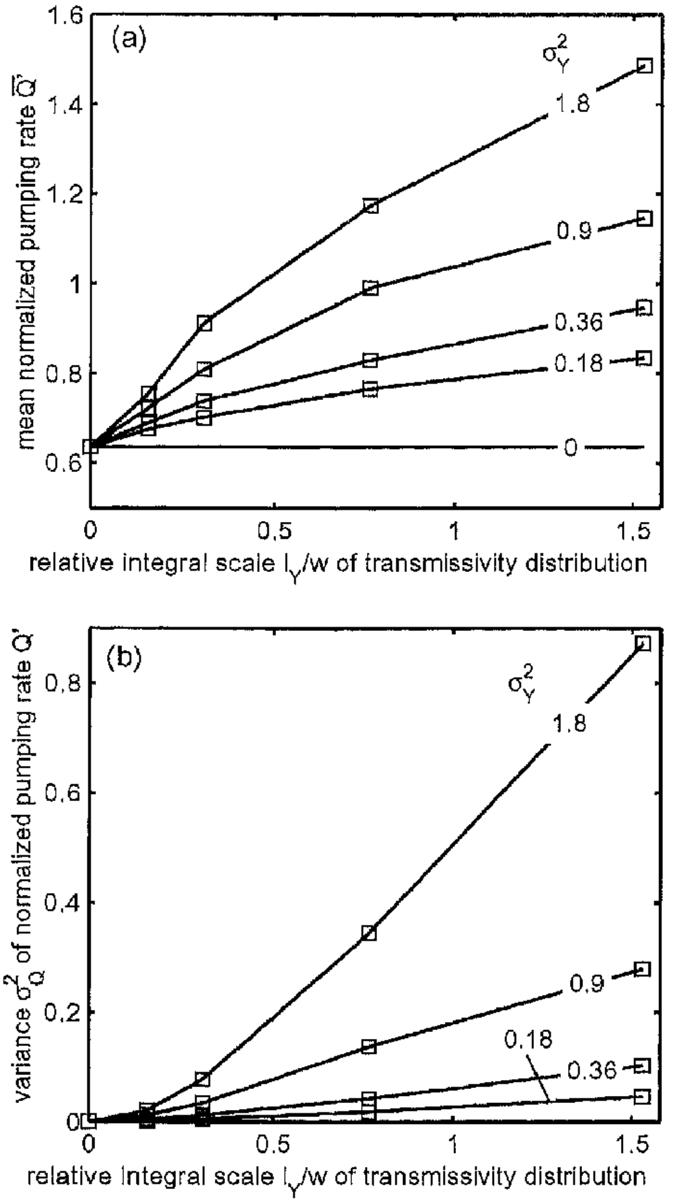

Figure 10. Setting D*—calculated $\overline{Q'}$ and $\sigma_{Q'}^2$ depending on the unconditioned transmissivity distribution of the aquifer (for ensembles of 500 realizations).

Taking into account the uncertainty inherent in the prediction of the required pumping rate, the benefit of additional physical barriers may be assessed by means of the probability of achieving a certain savings of the pumping rate with BPT. A corresponding analysis was performed by calculating the pumping rate reduction of BPT compared to CPT for each individual realization. By sorting these individual values of pumping rate reduction in ascending order, the distribution of the probability of reductions is obtained (Figure 11). Clearly, the shape of the probability curves depends on the degree of aquifer heterogeneity. Pumping rate savings for setting B* are generally lower than for setting D*, which is outperformed by setting E*. A comparison of Figures 11a and 11b reveals that pumping rate reduction is more sensitive to the integral scale than to the transmissivity variance. This is attributed to an increasing impact of high conductivity channels with an increasing integral scale. These channels are likely to either improve or worsen the performance of the CPT and BPT system in individual realizations, depending on their particular location. Therefore, they raise the variance of the probability distribution of pumping rate savings. Figure 11 also shows the pumping rate reduction, P_h, estimated for homogeneous conditions (horizontal lines). It is evident that the risk of overestimating the pumping rate reduction if predictions assume homogeneous conditions differs remarkably for the BPT settings. For setting E*, using P_h would overestimate the pumping rate reduction in 85% of the cases, while for setting B* only 40% of the realizations yield a pumping rate reduction lower than P_h.

Summary and Conclusions

A BPT has been proposed as an efficient contaminant plume management method that appears to be a promising alternative to CPT. Using established modeling techniques

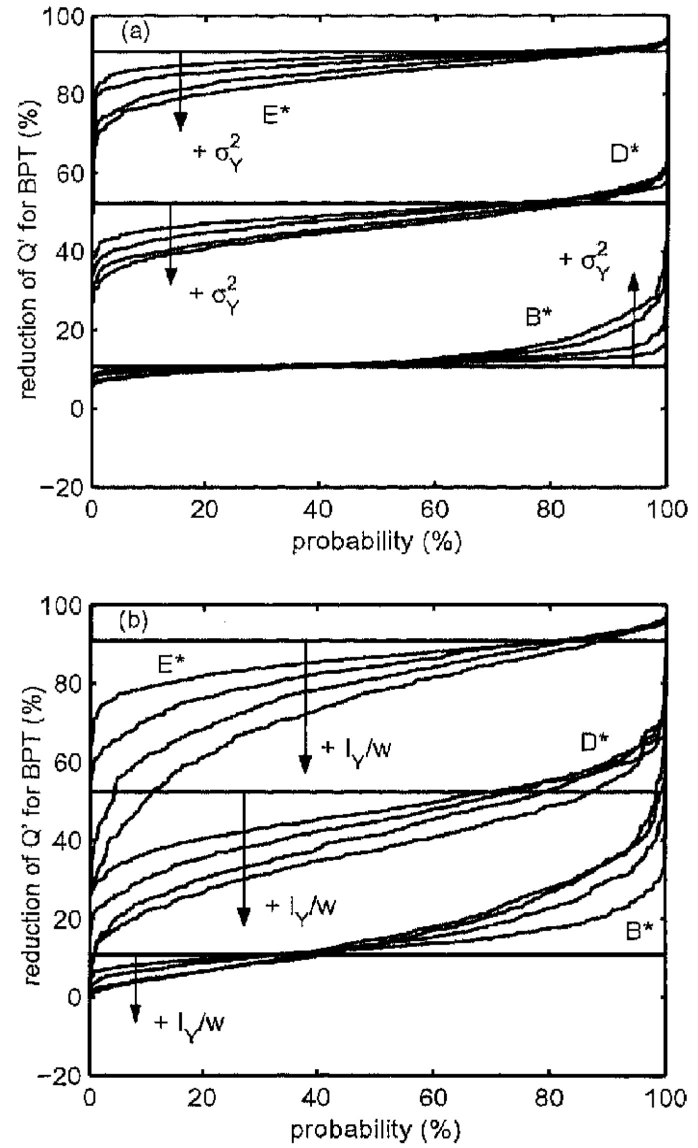

Figure 11. Probability curves for the reduction of pumping rate Q' by the installation of barriers (BPT settings B*, D*, and E*) in comparison to CPT. The orientations of the arrows indicate increasing values of σ_Y^2 (0.18, 0.36, 0.9, 1.8) in (a) and increasing values of I_Y/w (0.153, 0.306, 0.765, 1.53) in (b) starting from the results for the homogeneous aquifer (horizontal lines). For visualization issues, setting C* is neglected.

Table 3
Absolute Savings as $\Delta\ \overline{Q'}_{A\text{-}D*}$ of Setting D* Compared to Scenario A with Respect to Mean Pumping Rate, Depending on Integral Scale and Variance of the Lognormal Transmissivity Distribution

	Integral Scale I_Y/w			
Variance σ_Y^2	0.153	0.306	0.765	1.53
0.18	0.67	0.67	0.69	0.70
0.36	0.67	0.69	0.72	0.72
0.9	0.67	0.73	0.80	0.79
1.8	0.69	0.76	0.84	0.89

for flow (MODFLOW) and transport (MODPATH), the performance of BPT systems has been assessed by means of an advective control approach. The pumping rate required to capture a given contaminated area was considered as assessment criterion. CPT and BPT scenarios are first compared for homogeneous aquifer conditions in order to gain a detailed assessment of numerous BPT configurations, and to quantify the effect of the major decision factors. It is shown that the application of additional hydraulic barriers yields a respectable reduction of the pumping rate required for complete capture. This effect is governed by the relative position of barrier(s) and the pumping well. None of the scenarios examined here has been found to be the universal ideal solution but, in each scenario, the optimal configuration depends on the total barrier length that is applied.

A Monte Carlo analysis based on unconditioned realizations of spatial transmissivity distributions in heterogeneous aquifers was used to give insight into the hydraulic efficiency and system reliability in heterogeneous aquifers. Elasticity curves were calculated that reflect the tradeoff between required pumping rates to control the contamination and the performance reliability (the probability of achieving control) of CPT and BPT. These curves enable the planner to decide whether increasing a barrier length and thus investing more money leads to a reasonable increase of the performance reliability. It is shown that additional physical barriers tend to reduce not only the mean pumping rate, but also the spread of the pdf and, therefore, the uncertainty of the required pumping rate required for capture. These findings emphasize that there are two basic actions one can take when dealing with uncertainty arising from aquifer heterogeneity—reducing the uncertainty by further site investigation or selecting a technology less sensitive to probable variations of transmissivity.

The methodology presented in this paper provides hydraulic performance data for CPT and BPT as dimensionless figures. Therefore, provided some basic premises are fulfilled, the results of this study can be transferred conveniently to other cases, including pump-and-treat systems already in operation. The transfer is possible for homogeneous as well as heterogeneous aquifers, but it is limited to two-dimensional scenarios.

Please note that the assessment focuses on contamination control rather than on the extent of mass removal. As partial containment of the contaminated area changes flow conditions and velocities, it will influence mass removal rates from the source of contamination into ground water. Hence, the efficiency of the presented BPT systems in terms of mass removed is likely to be different compared to the efficiency in terms of minimal pumping rate. Options that appear to be most efficient in this study may not be the most efficient with respect to the extent of mass removal. However, due to the general limitation of mass transfer from residual contaminant phases into ground water, in many cases it might be advisable to focus on contaminant control, as considerable mass removal may not be achievable regardless of whether a CPT or BPT system is applied.

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